

GROUND BASED STUDIES OF THERMOCAPILLARY FLOWS IN LEVITATED DROPS

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ABSTRACT: Analytical studies along with ground-based experiments are presently being carried out in connection with thermocapillary phenomena associated with drops and bubbles in a containerless environment. The effort here focuses on the thermal and the fluid phenomena associated with the local heating of acoustically levitated drops, both at 1-g and at low-g. In particular, the Marangoni effect on drops under conditions of local spot-heating and other types of heating are being studied.

With the experiments conducted to date, fairly stable acoustic levitation of drops has been achieved and successful flow visualization by light scattering from smoke particles has been carried out. The results include situations with and without heating. As a preliminary qualitative interpretation of these experimental results, we consider the external flow pattern as a superposition of three discrete circulation cells operating on different spatial scales. The observations of the flow fields also indicate the existence of a steady state torque induced by the streaming flows.

The theoretical studies have been concentrated on the analysis of streaming flows in a gaseous medium with the presence of a spherical particle undergoing periodic heating. A matched asymptotic analysis was carried out for small parameters derived from approximations in the high frequency range. The heating frequency being 'in tune' with the acoustic frequency results in a nonzero time-averaged thermal field. This leads to a steady heat flow across the equatorial plane of the sphere.

INTRODUCTION

The potential for advancing fundamental understanding of liquid undercooling phenomena with containerless experimentation is well recognized. In particular, at zero-g, a liquid can remain undisturbed and experience deep undercooling. This high degree of undercooling can promote certain types of crystal growth and at the same time provide homogeneity of the product. In this regard, there is a strong interest in understanding the basic thermodynamics of such processes as well as in the measurement of properties such as thermal conductivity and thermal diffusivity.

In the absence of gravity, the principal effect of heating is the variation of interfacial tension. This generates a tangential stress at the interface and leads to liquid motion, which is also known as the Marangoni effect. Since this type of motion is characterized by the strength of the stimulus as well as the fluid mechanical and the thermophysical properties of the sample, an observation of the thermally driven motion can be used to infer these material properties. For such an interpretation, a successful predictive model is required to go along with the experimental studies.

OBJECTIVES

The principal objectives consist of fundamental studies concerning the fluid mechanics of acoustically levitated drops with thermally driven motion. The long term goal is to obtain a better understanding of the thermodynamics of undercooled liquids and also to measure their thermophysical properties. For thermal measurements, the idea of levitating a liquid drop in an acoustic field, and spot-heating it over a small fraction of its area by a laser beam has been explored. By carrying out the measurements of the thermocapillary effects of such heating, it is possible to infer the thermal properties of the sample by theoretical analysis corresponding to the experiments.

Analytical Part

Under the current program for ground-based studies, analytical models of acoustically levitated drops with thermal interaction are being developed. These models deal with the unexplored aspects of convective transport that arise due to the interference by the acoustic field on the drops. Thus, for many cases in ground based studies, the drops are deformed to spheroidal shapes and call for new analytical studies on the thermoacoustics of such systems.

Numerical and perturbation solutions for the combined thermal and acoustic fields are being developed with the final aim of having a comprehensive model that would work in conjunction with the experiments. This requires the solution to the Navier-Stokes equations together with the energy equation. The analysis, while providing the interpretation of experimental data, will also be useful for the assessment of the necessity and the feasibility of a space experiment.

Experimental Part

The experimental problem of interest is the thermal response of a spot-heated levitated drop in a convective gas flow of varying intensity. The ultimate objective is to quantitatively determine the transient and steady-state temperature distribution on the drop surface as a function of time, sample physical properties, geometry, and of the input radiant energy. Although the final goal will be to carry out an experiment in microgravity, the current project is limited to ground-based investigations using proven experimental techniques in order to verify and to correlate with the theoretical work. Also included in the goals is the development of experimental methods for a potential future microgravity investigation.

SIGNIFICANCE

As discussed in the Introduction, containerless processing is useful for deep undercooling which facilitates the production of certain types of crystals with a high degree of uniformity. The ongoing research will provide fundamental understanding of the Marangoni flows associated with localized heating of levitated drops. In addition, a comprehensive theoretical and experimental system is being developed for the thermodynamic measurement and analysis of materials in containerless environments. For ground based studies where there is interference from the acoustic field, a rigorous numerical model will provide significant new information about the behavior of these complex systems. The new work on compound drops will play a fundamental role for a zero-g space experiment. Most importantly, the model development along with the experimental studies will represent fundamental groundwork for the measurement of thermophysical properties of undercooled liquids.

RESEARCH APPROACH

Analysis

The relevant problems can be mathematically described by the Navier-Stokes equations and the energy equation in a coordinate system suitable for the spherical or the spheroidal geometries. With a defined acoustic field and a quantified heat source, approximate analytical methods and numerical methods will be employed.

Asymptotic Methods: The perturbation expansions are useful when a small parameter can be identified. The various approximations being used are discussed below:

1. Weak acoustic field:

In this case, forced convection is negligible and thermally driven transport dominates. This

includes Marangoni convection along with heat conduction.

2. Low Marangoni number:

With $Ma \ll 1$, along with a weak acoustic field, the heat flow is conduction dominated. Such an analysis has been conducted for spot-heated spherical drops by Sadhal, Trinh & Wagner [1]. Presently, the analysis has been extended to oblate spheroids with axisymmetric spot heating.

3. High frequency acoustic field:

In a high frequency field, as is the case for ultrasonic levitation, various large and small dimensionless parameters have been identified. In particular, $\varepsilon = U_0/a\omega \ll 1$ along with $M^{-1} \ll 1$, where $M^2 = a^2\omega/\nu$, serve as suitable perturbation parameters. Here, U_0 is the velocity amplitude, ω is the frequency, ν is the kinematic viscosity and a is the particle length scale.

For application to the case of steady streaming motion around a rigid sphere of radius a , a standing acoustic field with a velocity distribution of the form, $U_\infty \cos(\omega\tau^*) \sin(2\pi z^*/\lambda)$ is considered. With the long wavelength approximation, $a\omega/c \ll 1$, and with the sphere positioned in the vicinity of the maximum wave velocity, the flow field in the distant neighborhood of the sphere can be assumed to be $U_\infty \cos(\omega\tau^*)$.

Numerical Methods: Outside the range of the above approximations, numerical treatment is necessary. In fact, even for the perturbation methods used, some cases of asymptotic matching have required numerical procedures. Finite difference techniques would be suitable for full numerical treatment of the Navier-Stokes and the energy equations.

For situations involving spheroidal drops, the numerical analysis in the relevant curvilinear coordinate systems would be quite appropriate. The success of this approach in heat conduction problems has lent considerable credence to such methods for the current investigation.

Experiments

In 1-g, ultrasonic and electrostatic levitators are being used in order to provide the levitation capability. The schematic description of the electrostatic-acoustic hybrid levitator is given in Figure 1. Oblate spheroidal *uncharged* drops up to about 8 mm in diameter can be levitated ultrasonically and the shape can be adjusted to nearly spherical by adjusting the static electric field. With electrostatic levitation of charged drops, their static shape can be adjusted from oblate to prolate depending on the magnitude of the charge and that of the electric field. In addition to providing a nearly spherical levitated drop, the hybrid system will be used to better control the rotational state of the sample.

At present, pure acoustic levitation experiments with flow visualization inside and outside the drop are being conducted. The principal components of the apparatus are the ultrasonic prestressed transducer-reflector combination and sheet illumination. The vertical ultrasonic standing wave is generated between the transducer radiating face and the opposed reflector which presents a concave axially symmetric curved surface to the incoming wave. The levitation region is enclosed in a transparent chamber and the flow visualization is carried out by means of light scattering on tracer particles from a 5 mW unpolarized He-Ne beam. For the external flow, the tracer particles are generated by burning incense sticks or cotton ropes, and have sizes ranging from 0.1 to 1.0 μm . For the internal flow, suspended reflecting flakes are used.

The major difficulty in 1-g is with the adjustment of the ultrasonic field in order to cancel out any residual solid-body or differential rotation of the drop so as to resolve the inner thermocapillary

flows. Partial success has been achieved in the area of rotation control. Residual drop rotation rate of less than 0.1 rps can be obtained for short periods of about 30 sec, interrupted by random slow rotation periods with velocities up to 0.5-1.0 rps. Empirical adjustments of the levitator and the drop parameters can provide long duration periods with very low rotation rate (less than 0.5 rps). This rotation problem is very much reduced in low gravity, as observed during KC-135 tests.

RESULTS

Analysis

A detailed analysis has been carried out to examine the process of convective heat transfer due to acoustic streaming induced by a sound field about an isolated sphere which is subject to time-periodic temperature fluctuations. The important feature of interest in the present study is the energy transport phenomenon emanating from the time-independent contribution of the convective term due to the interactions of the thermal oscillations with the acoustic field.

With the approximations as listed under Research Approach, for sufficiently large frequencies, a thin Stokes layer region on the surface of the sphere constitutes the inner solution for the flow field which is then matched with a suitable outer solution. The temperature field in the fluid is induced by thermal oscillations which, for the purposes of simplicity, are taken to be harmonic (at a single frequency) and of the form, $T_\infty + (\Delta T)_a \cos(\omega\tau^* + \gamma)$, with $(\Delta T)_a \ll T_\infty$. Since the acoustic field of frequency ω is taken to be 'tuned' with the thermal field, the interaction of the thermal oscillations and the acoustic field results in a nonzero time averaged steady convective transport of heat in the fluid. This is the principal effect being investigated in this study, with attention restricted to gases with $Pr = O(1)$. For large streaming Reynolds numbers, $R_s = U_\infty^2/\omega\nu$, the matching of the inner Stokes layer with the outer field is through a thicker outer boundary layer.

The thermal disturbance is scaled in nondimensional form as the boundary condition, $\phi = \cos(\tau + \gamma)$, where $\tau = \omega\tau^*$ is the dimensionless time. With $\varepsilon \ll 1$ and $M \gg 1$, the procedures for inner and outer expansions, similar to Riley [2] and Gopinath [3] that have been used for fluid flow, are applicable for the energy equation. The major new result is the temperature field around the sphere which, in the inner region, has the perturbed form, $\Phi = \Phi_0 + \varepsilon(\Phi_{1s} + \Phi_{1u}) + \dots$, where the subscripts u and s refer to the unsteady and the time-averaged steady components, respectively. The calculations in the inner region together with matching in the outer thicker boundary layer region yield

$$\Phi_0 = e^{-\eta\sqrt{Pr}} \cos(\tau + \gamma - \eta\sqrt{Pr}) \quad (1)$$

$$\begin{aligned} \Phi_{1s} = & \frac{3\mu}{2} e^{-\eta\sqrt{Pr}} \left[\sqrt{Pr}(1 - \eta) \cos(\gamma - \eta\sqrt{Pr}) - (2 + \eta\sqrt{Pr}) \sin(\gamma - \eta\sqrt{Pr}) \right. \\ & \left. + \frac{Pr\sqrt{Pr}}{(1 + Pr)^2} e^{-\eta} \left\{ (1 - Pr) \cos(\gamma + \eta - \eta\sqrt{Pr}) + 2\sqrt{Pr} \sin(\gamma + \eta - \eta\sqrt{Pr}) \right\} \right] + \mu \Phi_{1\infty}(Pr, \gamma), \end{aligned} \quad (2)$$

where

$$\Phi_{1\infty}(Pr, \gamma) = \frac{3}{2} \frac{\sqrt{9Pr + 4}}{(1 + Pr)} \sin(\gamma - \gamma_0) \quad \text{with} \quad \tan \gamma_0 = \frac{\sqrt{Pr}(1 + 3Pr)}{2(1 + 2Pr)}, \quad \text{and} \quad \eta = (r-1) \frac{M}{\sqrt{2}}. \quad (3)$$

Together with this steady temperature field, there is a corresponding heat flux at the surface of the sphere, leading to an average Nusselt number across each hemisphere,

$$\frac{Nu_i}{\sqrt{R_s}} = \int_0^1 \left(-\frac{\partial \Phi_{1s}}{\partial \eta} \right)_{\eta=0} d\mu = -\frac{3}{2} \sin(\gamma_1 + \pi/4) \sin(\gamma - \gamma_1) \quad \text{with} \quad \tan \gamma_1 = \frac{\sqrt{Pr} - 1}{\sqrt{Pr} + 1}. \quad (4)$$

Experiments

Empty Chamber: According to the experimental results, a reflector with a smaller radius of curvature causes streaming to be directed towards the driver along the axis of symmetry, while the larger radius of curvature will generate flow in the opposite direction. It may be possible that with velocity antinodes more sharply defined closer to the reflector with a smaller radius, downward flow may be preferred. More investigation, however, is needed.

Isothermal Levitation: In Figure 2, a photograph of the video images of the streaming flow fields around a levitated liquid shell at 37 kHz is given. An axially symmetric vortex attached to the upper part of the sample can be faintly seen. Increasing the sound pressure causes flattening of the sample together with increasing the size of the secondary vortex. With the primary streaming field in the downward direction, the flow direction in the secondary vortex in the region along the central axis is away from sample. On the lower side of this vortex, it is towards the sample. The position of the vortex is on the upstream side of the sample which is opposite to the case of a simple flow past a sphere at intermediate Reynolds number. A satisfactory explanation is not immediately available.

In the case of a drop (as opposed to a shell), a sound pressure of 165 dB is required for levitation ($R_s = 460$). The secondary vortex is displaced to the lower half of the sample on the downstream side. Close inspection of the levitated drop reveals a solid body rotation at about 1 rps, with its axis perpendicular to the axis of the acoustic field. There is no available explanation for this residual torque which is clearly non-axisymmetric.

Heated Samples: A qualitative measurement of the effect of an acoustic standing wave on the temperature of a steadily heated thermistor gives an appreciation of the enhancement of the convective heat transfer from the sample to the environment. The main additional contribution to the flow field is the free convection which exhibits itself by splitting the lower set of eddies, stretching of the outermost eddy, and vortex shedding upon oscillation of the acoustic field, as seen in Figure 3.

CONCLUSION

The analytical and experimental studies of drops in an acoustic field have led to several new results. These are briefly summarized here.

1. The main results of the theoretical developments consist of the interaction of the acoustic field with the 'tuned' thermal oscillations of a spherical particle. In the case of a simple sinusoidal variation of the surface temperature of the sphere, there is net steady time-averaged temperature distribution and a corresponding heat flow across the equatorial plane of the sphere.
2. With levitated samples, flow visualization experiments have shown that the primary circulation in the acoustic field combines with the secondary streaming attached to the samples. The vortices generated by the presence of the sample have spatial dimensions on the scale of the sample size. At low sound pressures, the flow patterns can be represented by the simple superposition of the primary and the secondary flows. However, at high pressures, the interaction of the flows is not so straightforward.
3. A heated sample in an acoustic field experiences substantial cooling by the flow around the particle. This is found to be in qualitative agreement with the theoretical studies of Gopinath & Mills [4].

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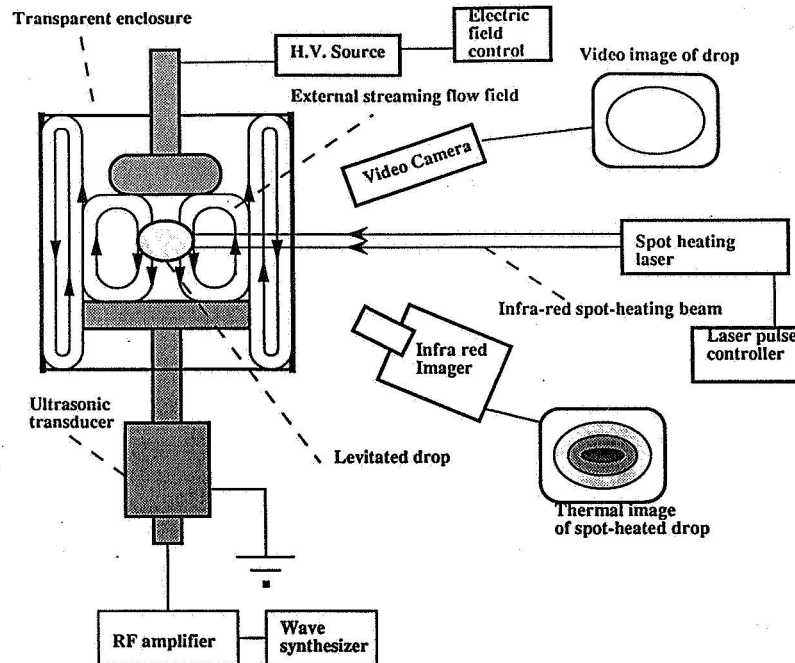


FIGURE 1: Schematic description of an electrostatic-acoustic hybrid experimental apparatus for the study of spot-heated levitated liquids.

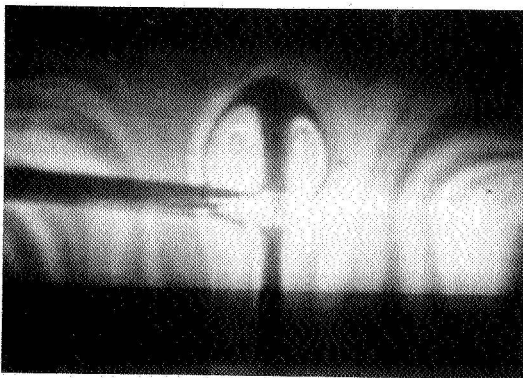


FIGURE 2: Flow visualization of streaming past a levitated liquid shell.

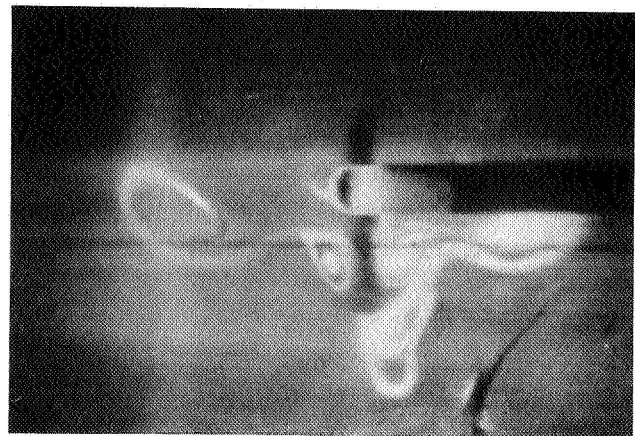


FIGURE 3: Flow field around a heated thermistor in 1-g.